Performance Indices Evaluation of Cascade Controller Tuning Method Based on Soft Oscillation Index

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***Abstract*—Control systems act as the nervous system for an industrial plant as they provide sensing, analysis, and control of various physical processes. Tuning them is the art of selecting values so that the controllers will be able to eliminate an error quickly and precisely to ensure the process variables stay within a pre-determined stability margin. That can be a painstaking process as it depends on the architecture of the control system and the controller design method. This paper describes a cascade-controller design based on soft oscillation index, with details for tuning them on the basis of stability margin. Using the same stability margin, this work provides analytical comparisons of performance indices in comparison with other well-known tuning methods.**

***Index Terms*—Cascade controller, controller tuning, performance indices, soft oscillation index**

I. Introduction

Controller tuning can be accomplished quickly and accurately using different techniques. While many engineers and technicians do resort to “tuning by feel”, most would admit that this approach yields inconsistent results. For example, if the tuning that is too slow, and the response will be sluggish and the controller will not handle upsets, and take too long to reach the setpoint. On the other hand, if the tuning that is too aggressive, and the loop will overshoot or become unstable. When a control system is at properly tuned, the process variability is reduced, efficiency is maximized, energy costs are minimized, and production rates can be increased.

An important feature is that the tuning strategy and efficiency are highly dependent on the architecture of the control system (e.g. one or more loops, centralized or distributed) and the controller design method (e.g. Ziegler-Nichols, Cohen-coon and Internal Model Control, etc.).

This paper focuses on the problem of tuning cascade controllers, which is available as a standard tool in almost all industrial process controller. In the standard cascade-control approach, one feedback loop is nested inside another feedback loop using two controllers. The controller of the inner loop is called the secondary (or slave) controller, and the controller of the outer loop is the primary (or master) controller. The rationale behind this configuration is that the fast dynamics of the inner loop enable fast attenuation of disturbances and minimize the possible effects of disturbances before they affect the primary output, which is the controlled variable of interest.

While there are a lot of studies for tuning single loop system, very few focus on tuning studies for the cascade systems, which are summarized below.

The usual approach involves first tuning the secondary controller by setting the outer loop open. The primary controller is then tuned while considering the action of the secondary controller on the inner loop. This two-step tuning procedure is time-consuming, because two test runs of the plant (step or relay test) are typically required [1], [2]. The sequential tuning procedure has been improved so that only a single experiment is conducted for tuning the two controllers simultaneously [3]-[8]. However, usually an off-line or ad hoc experiment must be performed in these methods. For example, Leva and Donida [3] performed a test with a relay cascaded to an integrator, and Mehta and Majhi [4] restricted the secondary controller to a P controller during the relay test. Meanwhile Veronesi and Visioli [8] proposed a simultaneous closed-loop automatic tuning method for cascade controllers based on a set-point step test. In another study [9], Jeng and Liao presented a method for tuning cascade control systems in which both primary and secondary controllers are tuned simultaneously by directly using plant data without resorting to process models. The required plant data are collected from a one-shot step test that can be conducted under either closed-loop or open-loop conditions. Their proposed design is to obtain the parameters of two Proportional-Integral-Derivative (PID) controllers such that the resulting inner and outer loops behave as closely to appropriately specified reference models as possible. The optimization problems related to the proposed design are derived. On the basis of the rationale behind cascade control, the

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secondary controller is designed to attenuate disturbance faster. The primary controller is designed to accurately account for the inner loop dynamics without requiring an additional test.

The very small number of studies for this compelling and highly practical problem proves that this could be a highly complicated problem. This paper describes the design of a cascade controller based on soft oscillation index, and their tuning based on the requirements of a stability margin. Analytical comparisons with other well-known tuning methods are given through a number of specific examples.

II. Background Theory

Consider a typical single closed-loop system as shown in Fig. 1 including process $O(s)$, controller $R(s)$, input z and output y.

The open loop transfer function is:

$$H(s) = R(s)O(s) \tag{1}$$

The closed-loop system in Fig. 1 has the transfer function of:

$$W(s) = \frac{R(s)O(s)}{1+R(s)O(s)} = \frac{H(s)}{1+H(s)} = \frac{C(s)}{D(s)} \tag{2}$$

and

$$O(s) = O_{PT}(s)e^{-\tau s} \tag{3}$$

where $O_{PT}(s)$ is polynomial element, τ is the dead time and $D(s)$ is named as characteristic polynomial.

The equation $1+H(s)=0$ or $D(s) = 0$ will have p pair of conjugate-complex roots type $s_i = -\beta_i \pm j\omega_i$ ($i = 1 \to p$). In [10] and [11] the factor $m_i=\beta_i/|\omega_i|$ is called oscillation index of the root s_i and $m_c=\min\{m_i\}$ is accepted as oscillation index of the system.

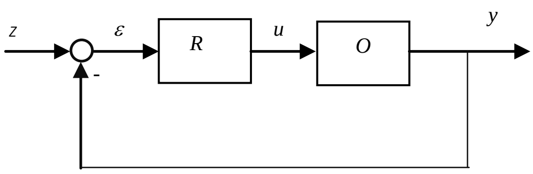

Fig. 1. A closed loop control system.

A. Soft Oscillation Index

The concept of soft oscillation index is a function of frequency [10], defined as below:

$$m(\omega) = m_0 \frac{1-e^{-\alpha\tau|\omega|}}{\alpha\tau|\omega|}, \alpha > 0 \tag{4}$$

where m_0 is the initial value of oscillation index function $m(\omega)$. With the given values of m_0, τ, α, the $m(\omega)$ is a function of only ω variable, it is a strictly decreasing from m_0 to 0 when ω increases from 0 to ∞. Hereafter, $m(\omega)$ is written simply as m.

B. Soft Boundary

The complex variable $s= -m|\omega|+j\omega$ is called soft variable. When ω varies from $-\infty$ to $+\infty$, the soft variable $s=-m|\omega|+j\omega$ will draw in the complex plane a symmetrical curve AOB (Fig. 2), named soft boundary. The roots located on the soft boundary have oscillation index equal to m while the roots on the left or right side of it have oscillation index higher or lower m respectively.

A system (Fig. 1) has a soft stability margin if all roots of $D(s)$ are on the left side or on the soft boundary [10], [11]. It also means that the system has a pair of solutions with the smallest fluctuation index (m_c) above or to the left of the soft boundary, the remaining roots will be on the left side of the soft boundary, then the system has a stability margin according to the soft boundary.

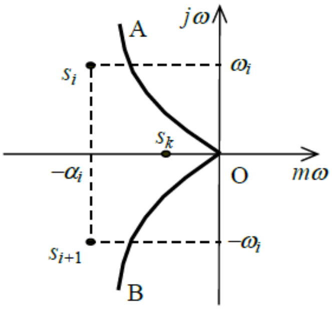

Fig. 2. Soft boundary

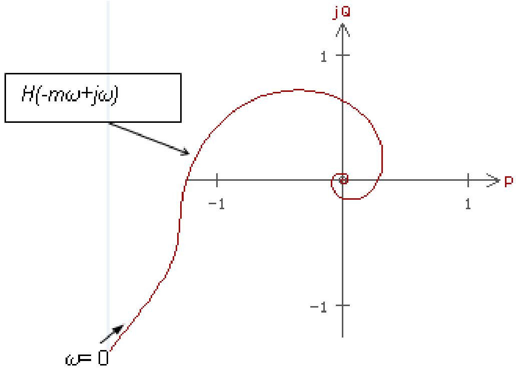

Fig. 3. Soft characteristic.

C. Soft Characteristic

If a soft variable is put into the open-loop transfer function $H(s)$, $H(-m\omega+j\omega)$ is called soft characteristic. Considering in the positive frequency domain ($\omega \geq 0$), the soft characteristic graph is shown in Fig. 3.

The criterion of soft stability margin [10], [11] is stated as follows: the necessary and sufficient condition for all the roots of the characteristic equation of the closed-loop and open-loop systems to be left side of the soft boundary is true that the soft characteristic of the open system does not surround point $(-1, j0)$.

D. Robust-Based Controller (RB)

In order to have the highest robustness, best performance and simplest structure, the system in Fig. 1 should be in the first order which has only one negative real root ($m=+\infty$). This means its transfer function will be

$$W(s) = \frac{1}{1+\theta s}, \ \theta > 0 \tag{5}$$

with θ is the inertia constant. So,

$$H(s)=\frac{W(s)}{1-W(s)}=\frac{1}{1+\theta s}\Big/\left(1-\frac{1}{1+\theta s}\right)=\frac{1}{\theta s} \quad (6)$$

$$R(s)=H(s)/O(s)=\frac{1}{\theta s}\ O(s)^{-1}=\frac{1}{\theta s}\ O_{PT}(s)^{-1}e^{\tau s} \quad (7)$$

To perform the controller, $e^{\tau s}$ will be eliminated. So,

$$R(s)=\frac{1}{\theta s}\ O_{PT}(s)^{-1} \quad (8)$$

It is called as the robust-based controller. With a known process $O(s)$, only θ is unknown and has to be chosen to achieve the required oscillation index m_c (robustness) and best performance of the system [11], [12]:

$$\theta=\frac{\tau e^{m_c\left(\frac{\pi}{2}-\operatorname{arctg} m_c\right)}}{\left(\frac{\pi}{2}-\operatorname{arctg} m_c\right)\sqrt{m_c^2+1}} \quad (9)$$

III. Cascade Control

Block diagram of a cascade control system is shown in Fig. 4, in which z is the set point, u_1 and u_2 are the outputs of the inner and outer controllers, respectively, y is the system output, d_1 and d_2 are the noise signals affecting the outputs of the object, and $R_{1,2}$, $O_{1,2}$, and $B_{1,2}$ are the transfer functions of the controllers, the objects and noise in the system respectively.

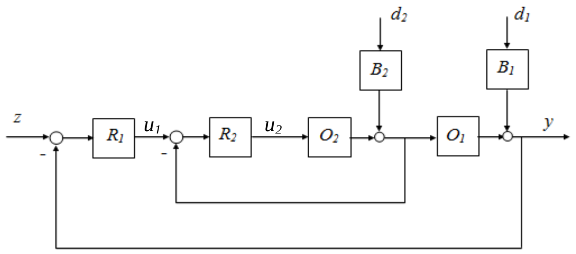

Fig. 4. Block diagram of cascade control system.

The inner loop is to eliminate noises that appear at the input side of the object. The faster the impact of the inner loop compared to the outer loop, the higher the noise reduction effect. Therefore, the point to get the feedback signal of the inner loop should be closer to the input of the object so that the object O_2 has less inertia and latency than object O_1 of the outer loop. The process in the inner loop is much faster than the outer loop so when the inner loop reacts, the outer loop is almost unresponsive and is considered an open-loop system. In this case, the inner loop can be viewed as an independent system.

Thus, controllers can be designed based on a robust viewpoint of a single loop system [11], [12], with the results as follows:

$$R_1(s)=\frac{1}{\theta_1 s}\ O_{1PT}(s)^{-1} \quad (10)$$

$$R_2(s)=\frac{1}{\theta_2 s}\ O_{2PT}(s)^{-1} \quad (11)$$

where $O_{iPT}(s)$ is a rational function of objects O_i (i=1, 2) and θ_1, and θ_2 are the inertia constants of the equivalent single-loop systems corresponding to the inner and outer loops:

$$\theta_1=\frac{\tau_1 e^{m_{c1}(\frac{\pi}{2}-\operatorname{arctg} m_{c1})}}{(\frac{\pi}{2}-\operatorname{arctg} m_{c1})\sqrt{m_{c1}^2+1}} \quad (12)$$

$$\theta_2=\frac{\tau_2 e^{m_{c2}(\frac{\pi}{2}-\operatorname{arctg} m_{c2})}}{(\frac{\pi}{2}-\operatorname{arctg} m_{c2})\sqrt{m_{c2}^2+1}} \quad (13)$$

where m_{c1} and m_{c2} are the oscillation indices of the dominant pairs of each loop (outer and inner loops), τ_1 and τ_2 is the delay time of O_1 and O_2 objects.

Each controller of (10) and (11) only needs to be tuned by a single parameter that is θ_1 and θ_2:

- If the objects O_1 and O_2 contain the transfer functions of the first/second order process with time delay, the amplifier with time delay or integrator process, then the received controllers $R_{1,2}(s)$ has the industry standard format such as I, PI, PID and PD controllers.
- In case of a rational function of the object, if the order of the denominator is greater than the order of the numerator by 3 or more, implement an improper transfer function using an order-compensate filter as follows:

$$\Phi_k(s)=\frac{1}{(1+0,1T_{\min}s)^q} \quad (14)$$

where q is the order of the filter so that the transfer function after compensation has order of the numerator is greater than the order of the denominator. $T_{\min}$ is the smallest time constant of the object.

IV. Tuning Controllers

A. Evaluation of the Oscillation Index of the Loops

From (9), where τ is a constant, we have:

$$\lim_{m_c\to\infty}\theta=\lim_{m_c\to\infty}\frac{\tau e^{m_c\left(\frac{\pi}{2}-\operatorname{arctg} m_c\right)}}{\left(\frac{\pi}{2}-\operatorname{arctg} m_c\right)\sqrt{m_c^2+1}}$$

$$=\tau\lim_{m_c\to\infty}\left[\frac{e^{m_c\left(\frac{\pi}{2}-\operatorname{arctg} m_c\right)}}{m_c\left(\frac{\pi}{2}-\operatorname{arctg} m_c\right)}\frac{1}{\sqrt{1+\frac{1}{m_c^2}}}\right]$$

$$=\tau\lim_{m_c\to\infty}\frac{e^{m_c\left(\frac{\pi}{2}-\operatorname{arctg} m_c\right)}}{m_c\left(\frac{\pi}{2}-\operatorname{arctg} m_c\right)} \quad (15)$$

However,

$$\lim_{m_c\to\infty}\left[m_c\left(\frac{\pi}{2}-\text{arctg}\,m_c\right)\right]=\lim_{m_c\to\infty}\frac{\frac{\pi}{2}-\text{arctg}\,m_c}{\frac{1}{m_c}} \tag{16}$$

$$=\lim_{m_c\to\infty}\frac{\frac{-1}{1+m_c^2}}{\frac{-1}{m_c^2}}=1$$

So,

$$\lim_{m_c\to\infty}\theta=\tau e^1 \tag{17}$$

The graph of $\theta - m_c$ is shown in Fig. 5.

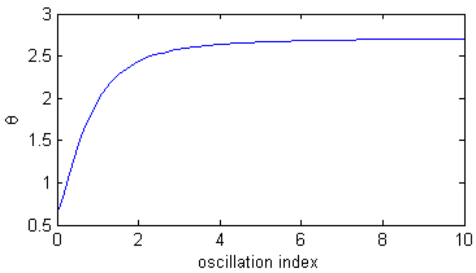

Fig. 5. $\theta \to e$ when $m_c \to \infty$ and τ=1.

According to (11), θ_2 is inversely proportional to the gain coefficient of the R_2 controller so the larger the θ_2, the smaller the gain factor leads to the smaller R_2 output signal. This output signal impacts the O_2 object, which is usually the actuators (e.g. regulating valves), so the signal must not exceed the threshold to avoid saturation. However, it was found that the bigger the m_c, the more robust the system is. Therefore, we must select the value m_{c2} so that it reaches the equilibrium with the threshold signal of actuator and $m_{c2} > 0$.

For cascade systems, the stability margin requirements are determined for the output signal at the outer loop, i.e. the m_{c1} oscillation index. However, for cascade control systems, in order to increase the robustness of the system, the inner loop must have a robustness greater or equal to the outer loop, and the oscillation index of the inner loop is greater or equal to the oscillation index of the outer loop ($m_{c2} \geq m_{c1} > 0$).

B. Tuning Cascade Controllers to Ensure Stability Margin of the System

As estimated above, the two control loops are considered independent. When the controllers are implemented in the system, they affect each other, so the system needs to be tuned to ensure the stability margin requirement.

Assuming that the system has the stability margin according to the soft oscillation index as (4), $H_1(-m\omega + j\omega)$ is the soft characteristic of the cascade control system, ($\omega \geq 0$). Then $H(-m\omega + j\omega) = P(\omega) + jQ(\omega)$, where $P(\omega)$ is the real part, $Q(\omega)$ is the imaginary part (Fig. 6).

Let ω^* be the frequency at which the soft characteristic curve intersects the real axis (Fig. 6):

$$H(-m\omega^* + j\omega^*) = P(\omega^*),\quad Q(\omega^*) = 0 \tag{18}$$

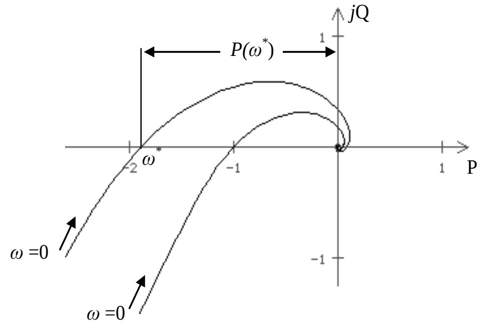

Fig. 6. Soft characteristic of open-loop cascade system.

From the formula above, letting the soft characteristic curve cut the horizontal axis at the point (–1, j0) at the frequency ω^*, the scale coefficient can be calculated from the following equation:

$$H_k(-m\omega^* + j\omega^*) = KP(\omega^*) = -1 \Rightarrow K = \frac{-1}{P(\omega^*)} \tag{19}$$

So in order for the system to reach the stability margin (based on the soft stability margin criterion), the soft characteristic curve must be adjusted to cut the horizontal axis at positions between 0 and (–1+j0), meaning that coefficient K' has to be bigger than coefficient K above.

On the other hand, consider a cascade control system as an equivalent single-loop structure (see the following Fig. 7).

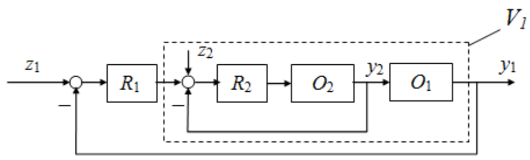

Fig. 7. Two-loops control system and equivalent single-loop structure to R_1 controller.

The transfer function of the open outer-loop system is:

$$H(s) = R_1(s)V_1(s) \tag{20}$$

where V_1 is the equivalent object of the outer-loop (including the inner-loop and O_1 object).

At frequency ω^*, if the soft characteristic changes by a quantity K', then the gain coefficient of $R_1(s)$ changes by an amount equal to K'.

So, the gain coefficient of the controller can be adjusted by a number of K' to ensure the system's the soft stability margin.

V. Simulation Examples and Performance Indices Evaluation

Consider the process given by object transfer functions [8], [9] and the requirement to ensure a stability margin corresponding to the soft oscillation index having α = 3 and m_0 = 1.35 as follows:

$$O_2(s) = \frac{1}{s+1}e^{-0.5s},\quad O_1(s) = \frac{1}{s(1+10s)(1+2s)}e^{-3s}$$

$$m(\omega) = 1.35\frac{1-e^{-3|\omega|}}{3|\omega|}$$

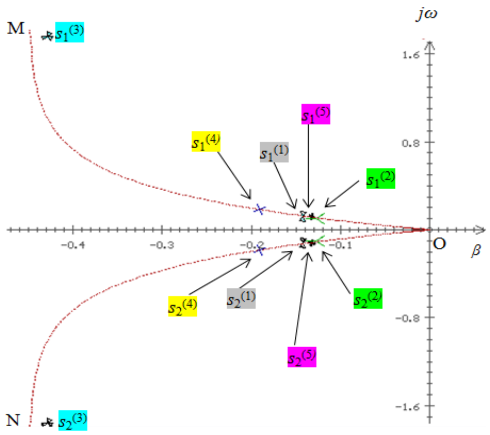

Fig. 8. Soft boundary MON corresponding to the soft oscillation index having $\alpha = 3$; $m_0 = 1.35$ and the dominant pair position.

Then $s = -m\omega + j\omega$ runs on the soft boundary MON on Fig. 8.

The requirement of stability margin is set in this case to compare with 2 methods [8], [9]. Both of these methods give the dominant pair located on the soft boundary.

According to the method of Jyh Cheng Jeng [9], the designed controllers will be:

$$R_2(s) = 1.336\left(1 + \frac{1}{0.833s}\right)$$

$$R_1(s) = 0.0768(1 + 10.64s)$$

The dominant pair $s_1^{(1)}$, $s_2^{(1)}$ of the system when using this method are:

$$s_{1,2}^{(1)} = -0.142 \pm j0.118$$

This dominant pair is on the soft boundary MON (Fig. 8) at frequency $\omega = 0.1118$.

According to the method of Veronesi and Visioli [8], the designed controllers will be

$$R_2(s) = 1.377\frac{(1+0.252s)(1+1.1s)}{s(1+0.076s)}$$

$$R_1(s) = 0.079\frac{1+9.79s}{1+0.098s}$$

The dominant pair $s_1^{(2)}$, $s_2^{(2)}$ of the system when using this method are

$$s_{1,2}^{(2)} = -0.127 \pm j0.1$$

This dominant pair is on the soft boundary MON (Fig. 8) at frequency $\omega = 0.1$.

According to the design method of Robust-based controller (RB), the design should ensure that the dominant pair is on the left or at least on the soft boundary.

- Calculate the inner-loop controller

With the oscillation index of the dominant pair for this round of $m_{c2} = 0.6$, the delay time of the inner object is $\tau_2 = 0.5$.

Replace these values into (13) and we get: $\theta_2 = 0.7721$. R_2 controller according to (11) is

$$R_2(s) = 1.295\frac{1+s}{s}$$

- Calculate the outer-loop controller

With the oscillation index of the dominant pair for this round of $m_{c1} = 0.5$, the delay time of the outer object is $\tau_1 = 3$.

Replace these values into (12) and we get: $\theta_1 = 4.2157$. R_1 controller according to formula (10) is

$$R_1(s) = 0.2372\frac{(1+10s)(1+2s)}{(1+0.2s)^2}$$

The transfer function of order-compensate filter according to (14) is

$$\Phi_1(s) = \frac{1}{(1+0.2s)^2}$$

The dominant pair $s_1^{(3)}$, $s_2^{(3)}$ (Fig. 8) of the system when using this method are:

$$s_{1,2}^{(3)} = -0.429 \pm j1.759$$

This dominant pair is located on the right side of the soft boundary at the frequency $\omega = 1.759$ (Fig. 8). The system does not guarantee stability margin according to a given soft oscillation index.

Continue to tune the amplification factor of R_1 controller according to (19) so that the system ensures stable reserve. We get the new controller is:

$$R_1(s) = 0.12\frac{(1+10s)(1+2s)}{(1+0.2s)^2}$$

The dominant pair $s_1^{(4)}$, $s_2^{(4)}$ of the system is now:

$$s_{1,2}^{(4)} = -0.191 \pm j0.186$$

This dominant pair on the soft boundary (Fig. 8) ensures the system has the stability margin according to requirements.

For ease of comparison, the robust-based controller is converted to PID controllers (noted by PID-RB). The conversion steps are as follows:

- The R_2 controller remains the same because it is a PI with $K_{c2} = 0.9429$; $\tau_{i2} = 1$.
- Modeling O_1 object into a first-order integral inertia system with delay by Cleft-overstep optimization algorithm [10], we get a new transfer function:

$$O_1'(s) = \frac{1}{s(1+10.344s)}e^{-4.683s}$$

With the oscillation index of the dominant pair for this round of $m_{c1} = 0.5$, the delay time of the inner object is $\tau_1 = 4.683$.

Replace these values into (12) and we get: $\theta_1 = 6.5808$. R_1 controller according to formula (10) is

$$R_1(s) = 0.08(1 + 10.344s)$$

TABLE I: PERFORMANCE INDICES OF THE SYSTEM OUTPUT WITH INPUTS: SETPOINT, DISTURBANCE d_2, DISTURBANCE d_1

Method	Overshoot (Setpoint)	SettlingTime (Setpoint)	ISE (Setpoint)	Peak (d2)	SettlingTime (d2)	ISE (d2)	Peak (d1)	SettlingTime (d1)	ISE (d1)
Jyh- Cheng Jeng	0%	23.39	9.652	0.76	40.97	0.713	0.5	20.67	2.414
Veronesi and Visioli	2.7%	22.76	9.949	0.801	38.31	0.647	0.5	20.4	2.488
RB	4.1%	13.9	6.885	0.827	29.94	0.371	0.5	12.8	1.722
PID RB	1.7%	21.55	9.652	0.79	37.27	0.664	0.5	19.85	2.414

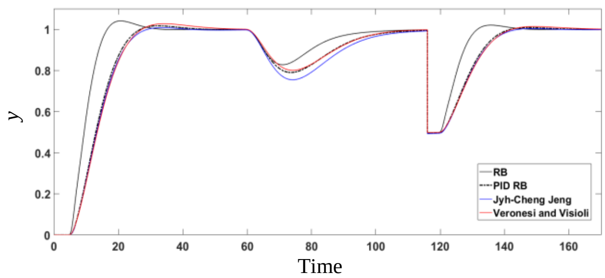

Fig. 9. Losed-loop response of the system.

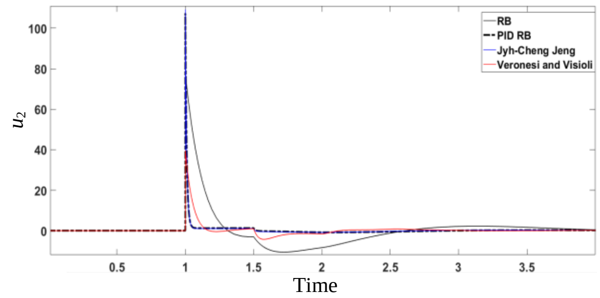

Fig. 10. Control signal u_2.

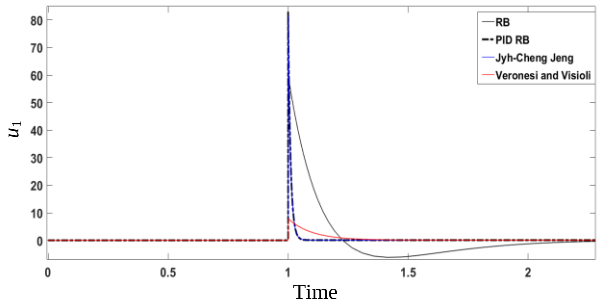

Fig. 11. Control signal u_1.

The dominant pair $s_1^{(5)}$, $s_2^{(5)}$ of the system when using this method are

$$s_{1,2}^{(5)} = -0.153 \pm j0.069$$

This dominant pair on the soft boundary at the frequency ω = 0.106 (Fig. 8). The system guarantees stability margin according to a given soft oscillation index.

Fig. 9 shows the closed-loop response to a unit-step set-point change at t = 0 followed by step disturbance inputs d_2= –0.5 at t = 55 and d_1= –0.5 at t = 115.

As shown in Fig. 9, the closed-loop response of the system will give the best performance when using the original robust-based controller with the indexes as SettlingTime (to fall to within 5% of y), Overshoot, Peak, Integral Square Error (ISE). PID-RB controllers give also performance indices better than those of Jyh-Cheng Jeng and Veronesi *et al*. Specific values are shown in Table I.

Fig. 10 and Fig. 11 show the outputs of the controllers R_2 and R_1. The graphs show that the original robust-based controllers give the best closed-loop performance but the control signal is very and is large stretched out, which is not good for the actuator in the system. The PID-RB controllers produce very small control signals and especially this method gives very little deviation from the Jyh-Cheng Jeng controller.

VI. CONCLUSIONS AND PERSPECTIVES

Designing and tuning cascade controllers are a common problem in controlling many industrial processes. This paper presents analysis comparisons of tuning methods to cascade controllers based on ensuring the stability margin for the system.

This paper describes the design and tuning of cascade controllers based on soft oscillation index. Based on a requirement of the system's stability margin, the controller coefficients are selected and adjusted. Afterwards, analytical comparisons of performance indices with the recent tuning methods are given.

The design and calibration method based on the soft oscillation index will be used to study for cascade control system with the number of loops greater than 2. The algorithm should also be packaged as a toobox that can be integrated into Matlab software.

This work is also a good reference for research directions such as smart embedded systems [13], [14], control theory [15], [16], etc.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest in the subject matter or materials discussed in this manuscript.

AUTHOR CONTRIBUTIONS

Both authors discussed ideas and solutions for the problem; Vu Thu Diep did the programming, and all authors had approved the final version.

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